Energy and the first law of thermodynamics

Part I

Module Overview / Introduction

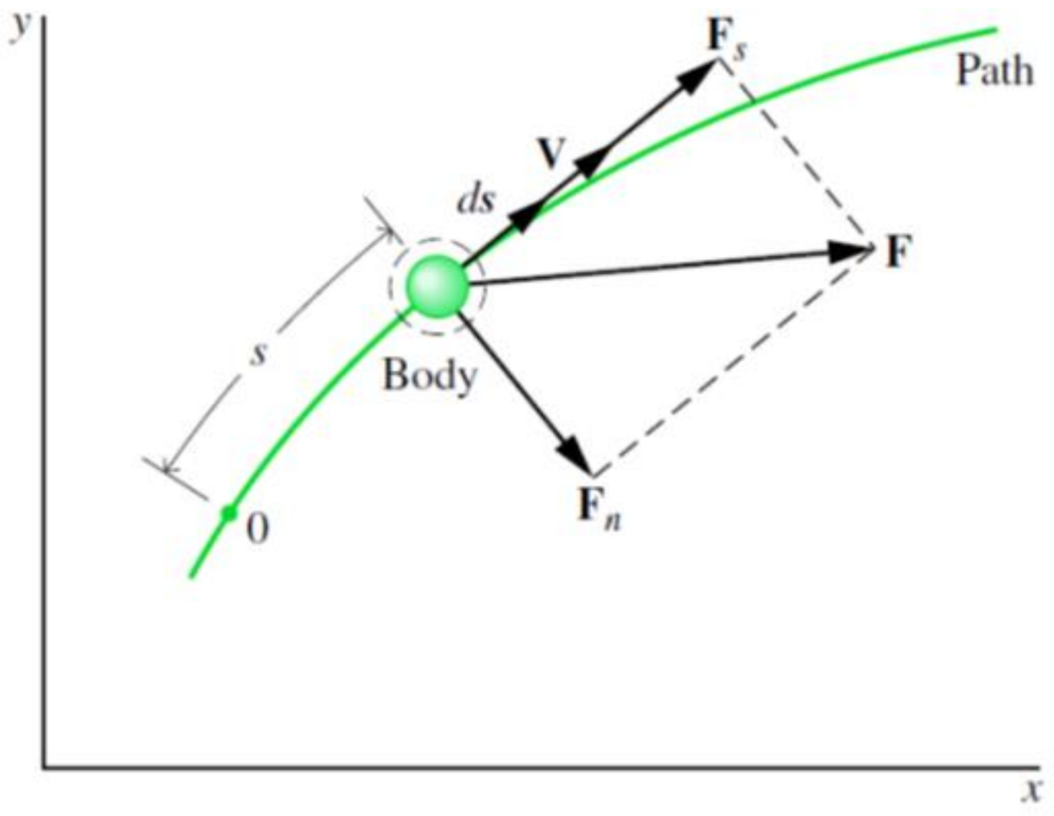
- This module introduces two basic concepts of thermodynamics, which are work and heat
- The release of energy can be used to provide heat when a fuel burns in a furnace, to produce mechanical work when a fuel burns in an engine, and to generate electrical work when a chemical reaction pumps electron through a circuit
- In thermochemistry, we encounter reactions that can be harnessed to provide heat and work, reactions that liberate energy which is squandered but which give products we require, and reactions that constitute the processes of life

Lesson 1: Basic Concept of Work

- The expansion of a gas that pushes out a piston and raises a weight
- A chemical reaction that drives an electric current through a resistance also does work, because the same current could be driven through a motor and used to raise a weight
- When work is done on an otherwise isolated system , the capacity of the system to do work is increased; in other words, the energy of the system is increased
- When the system does work , the energy of the system is reduced, and it can do less work than before
- When the energy of a system changes as a result of a temperature difference between the system and its surroundings we say that energy has been transferred as heat

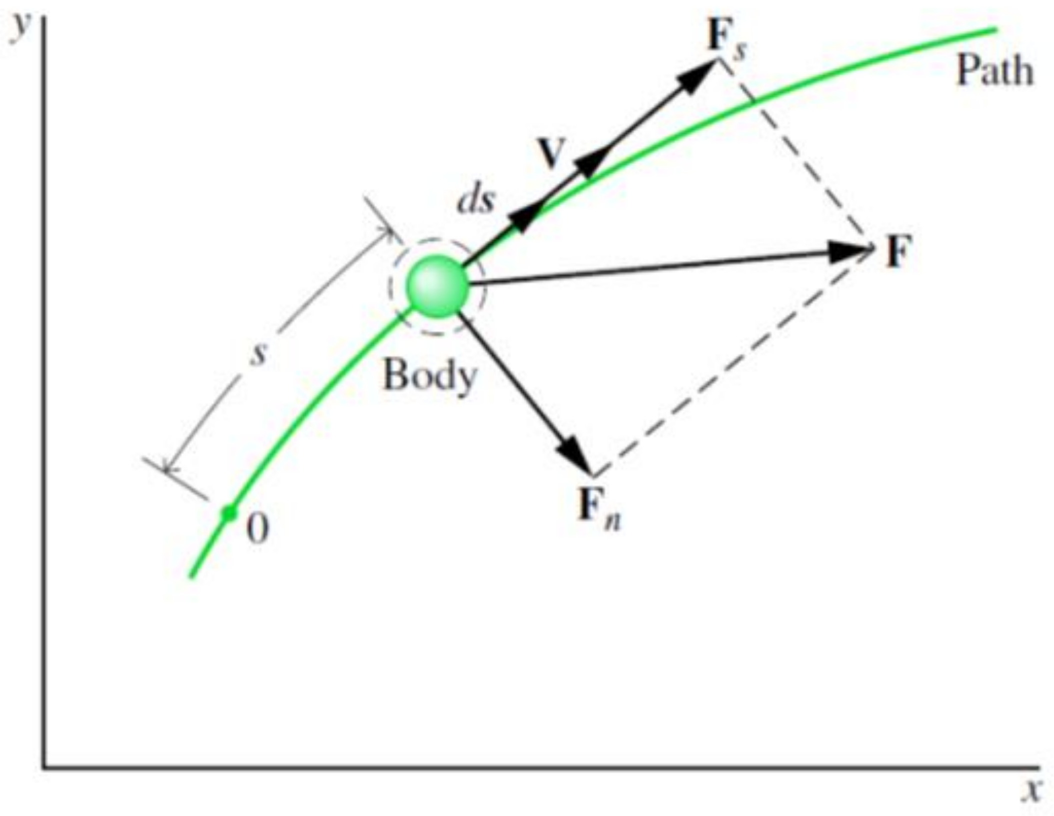
Subtheme 1.1: Work and Kinetic Energy

- Figure represents the path of a body of mass m moving relative to the x–y coordinate frame shown
- The body is acted upon by a resultant force, which may vary in magnitude from location to location along the path.
- The resulting force is split into a component F_s along the path and a component F_n normal to the path
- The effect of the component F_s is to change the magnitude of the velocity, whereas the effect of the component F_n is to change the direction of the velocity



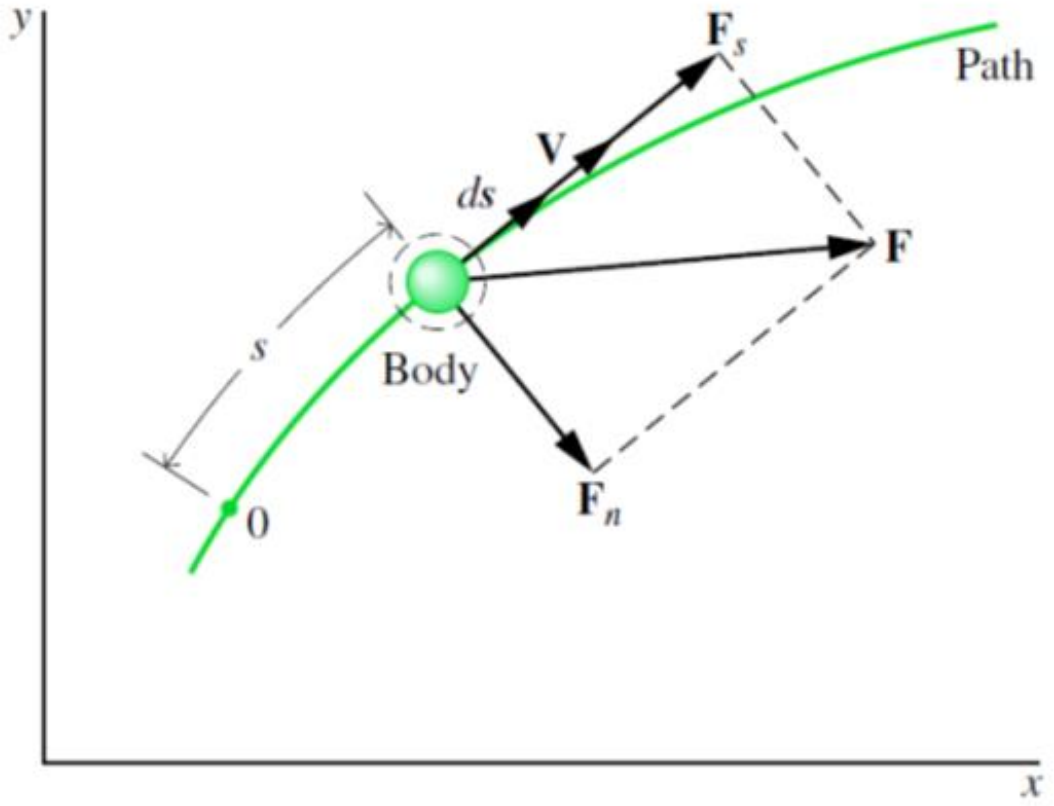
Subtheme 1.1: Work and Kinetic Energy

- As shown in Figure, *s* is the instantaneous position of the body measured along the path from some fixed point denoted by 0.
- Since the magnitude of *F* can vary from location to location along the path, the magnitudes of F_S and F_n are, in general, functions of *s*.



Subtheme 1.1: Work and Kinetic Energy

- Let us consider the body as it moves from $s = s_1$, where the magnitude of its velocity is V_1, to $s = s_2$, where its velocity is V_2.
- Assume for the present discussion that the only interaction between the body and its surroundings involves the force F.



Subtheme 1.1: Work and Kinetic Energy

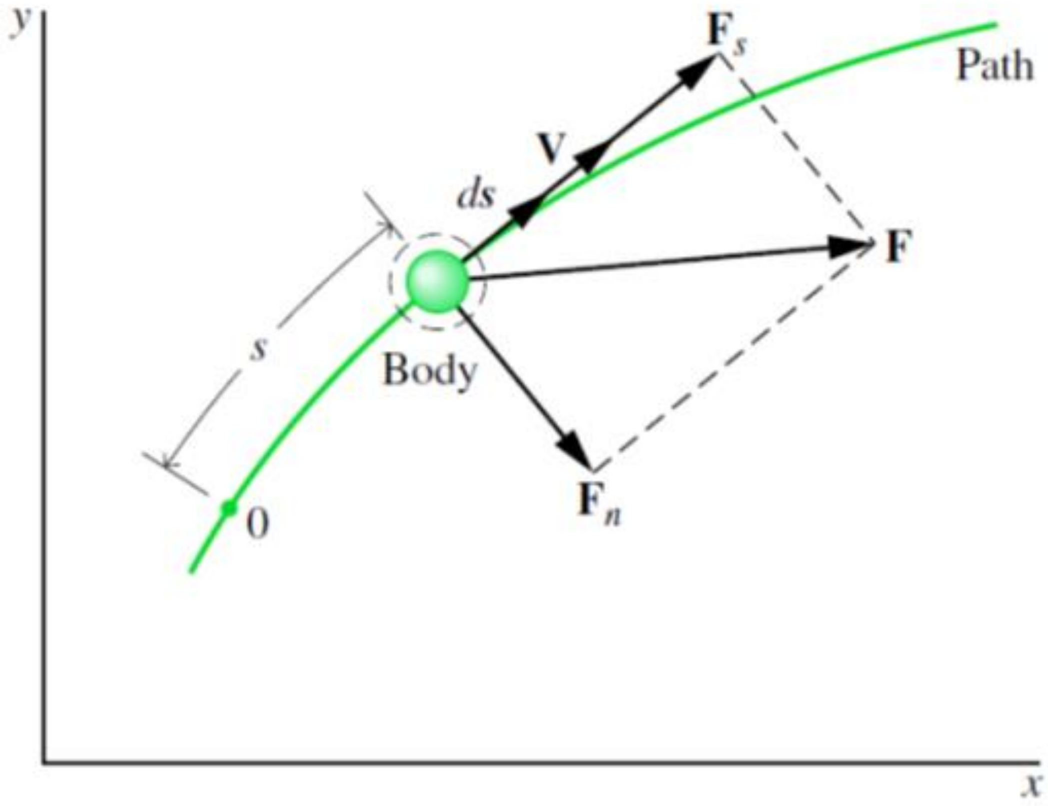
- By Newton's second law of motion, the magnitude of the component F_s is related to the change in the magnitude of V by:

$$F_s = m\frac{dV}{dt}$$

- Using the chain rule and due to $V(s)$ and $s(t)$, this can be written as:

$$F_s = m\frac{dV}{ds}\frac{ds}{dt} = mV\frac{dV}{ds}$$

where $V = ds/dt$



Subtheme 1.1: Work and Kinetic Energy

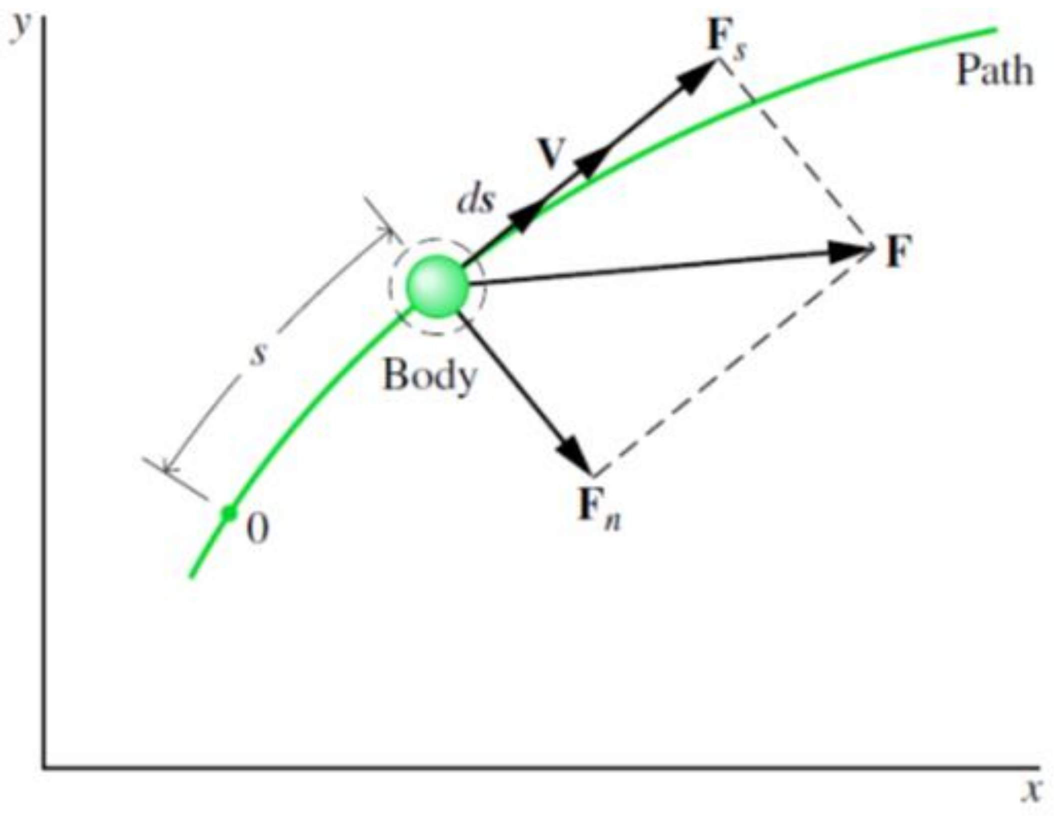
- Rearranging and integrating from s_1 to s_2 gives:

$$\int_{s_1}^{s_2} F_s ds = \int_{V_1}^{V_2} mV dV = \frac{1}{2} mV^2 \Big|_{V_1}^{V_2} =$$

$$\frac{1}{2} m\left(V_2^{\,2} - V_1^{\,2}\right) = \Delta KE_2 - \Delta KE_1 = \Delta KE$$

The quantity $(1/2)mV^2$ is the kinetic energy, KE, of the body. Kinetic energy is a scalar quantity. Hence, the change in the kinetic energy of the body is ΔKE.

The first integral on the right is the work, W, of the force F_s as the body moves from s_1 to s_2 along the path.

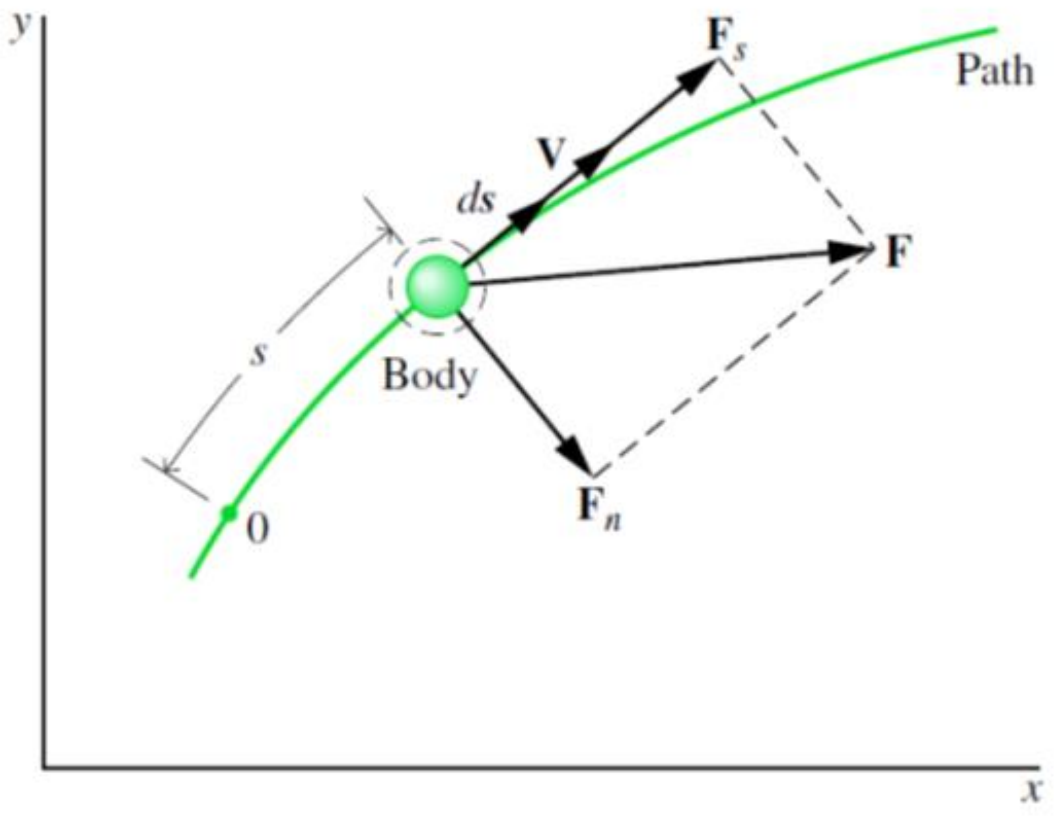


Subtheme 1.1: Work and Kinetic Energy

- Work is also a scalar quantity and it is related to the energy by:

$$W = \int_{s_1}^{s_2} F_s ds = \Delta KE$$

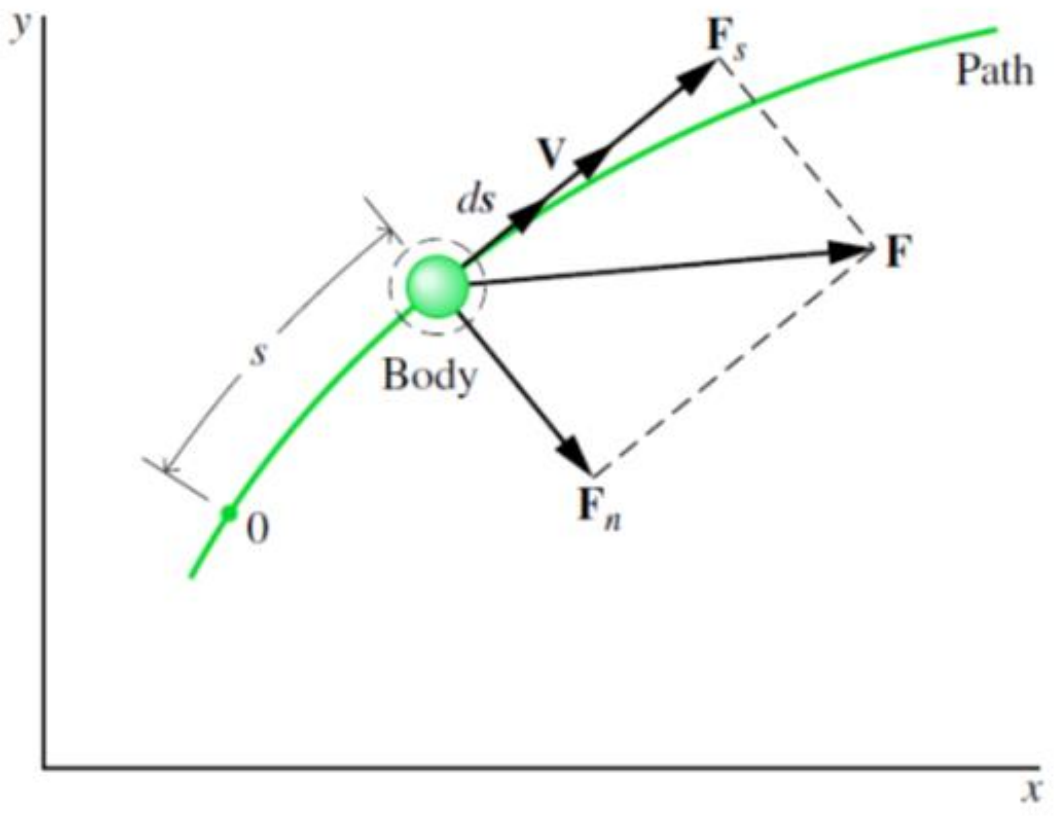
This equation states that the work the resultant force exerts on the body equals the change in its kinetic energy. When the body is accelerated by the resultant force, the work done on the body can be considered a transfer of energy to the body, where it is stored as kinetic energy.



Subtheme 1.1: Work and Kinetic Energy

- Kinetic energy can be assigned a value knowing only the mass of the body and the magnitude of its instantaneous velocity relative to a specified coordinate frame, without regard for how this velocity was attained. Hence, kinetic energy is a property of the body.

- Since kinetic energy is associated with the body as a whole, it is an extensive property. Work has units of force times distance. The units of kinetic energy are the same as for work. In SI, the energy unit is the newton-meter, Nm called the joule, J. It is frequently to use the kilojoule, $kJ = 1000J$.



Subtheme 1.1: Work and Kinetic Energy

- Work is also a scalar quantity and it is related to the energy by: Equation 4 states that the work the resultant force exerts on the body equals the change in its kinetic energy
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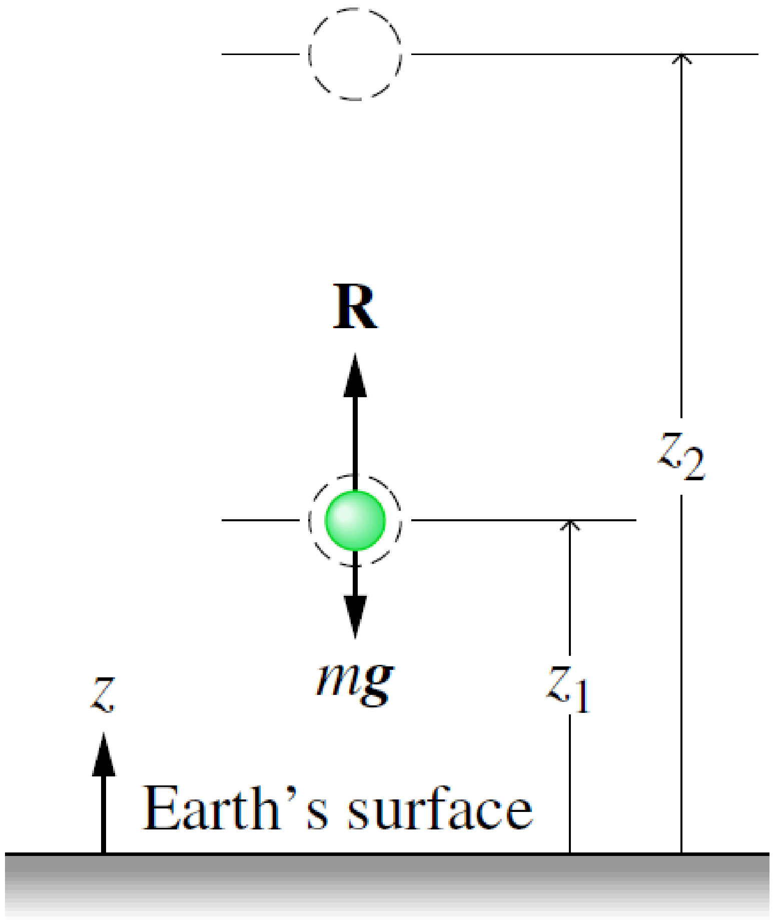
Subtheme 1.2: Work and Potential Energy

- Derived from Newton's second law, the equation gives a relationship between two defined concepts: kinetic energy and work
- In this section, it is used as a point of departure to extend the concept of energy
- Two forces are shown acting on the system: a downward force due to gravity with magnitude and a vertical force with magnitude representing the resultant of all other forces acting on the system
- The units for potential energy in the SI system are the same as those for kinetic energy and work
- Potential energy is associated with the force of gravity and is, therefore, an attribute of a system consisting of the body and the earth together

Subtheme 1.2: Work and Potential Energy

- Figure shows a body of mass m that moves vertically from an elevation z_1 to an elevation z_2 relative to the surface of the earth.
- Two forces are shown acting on the system: a downward force due to gravity with magnitude mg and a vertical force with magnitude R representing the resultant of all other forces acting on the system.

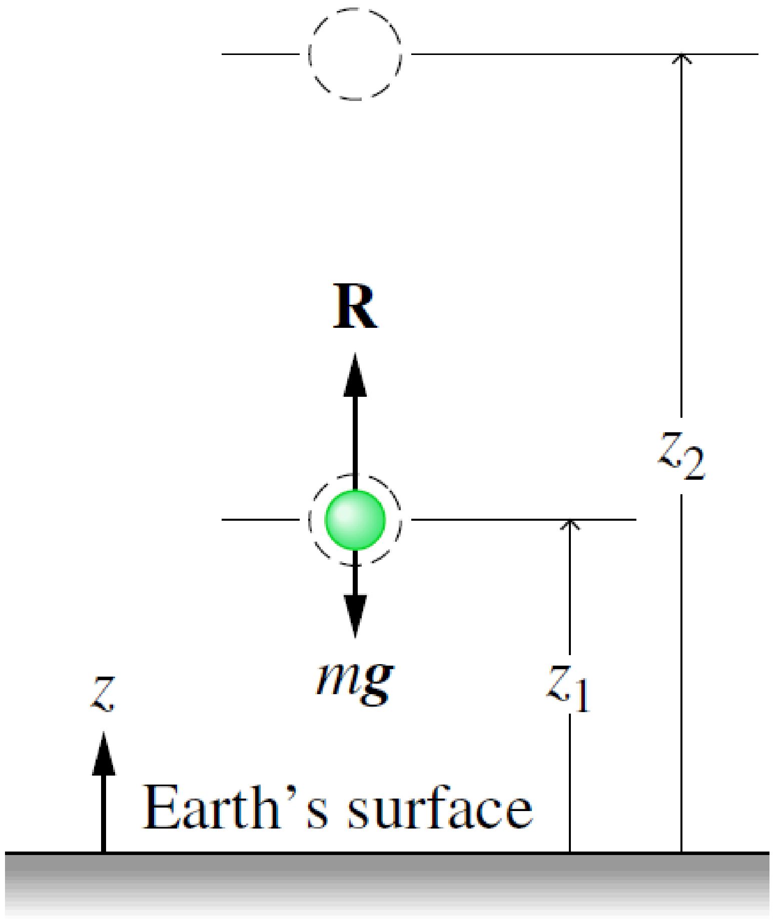


Subtheme 1.2: Work and Potential Energy

- The work of each force acting on the body shown in Figure can be determined by using the definition previously given. The total work is the algebraic sum of these individual values. The total work equals the change in kinetic energy. That is:

$$W = \int_{z_1}^{z_2} R dz - \int_{z_1}^{z_2} mg dz = \frac{1}{2} m(V_2^2 - V_1^2)$$

A minus sign is introduced before the second term on the right because the gravitational force is directed downward and z is taken as positive upward.



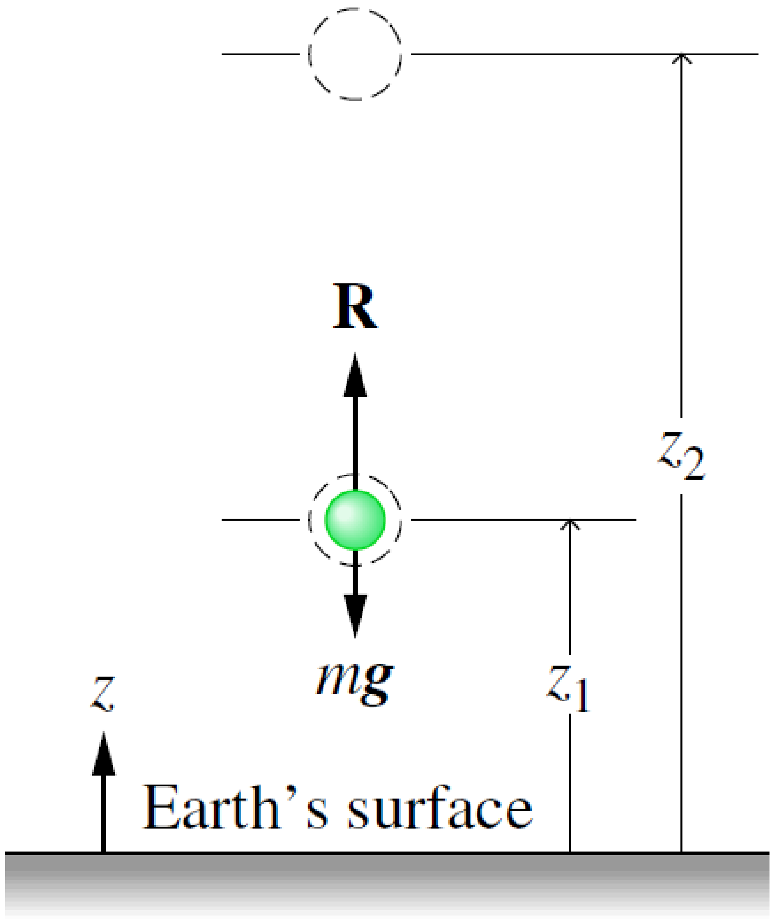
Subtheme 1.2: Work and Potential Energy

- The first integral on the right represents the work done by the force R on the body as it moves vertically from z_1 to z_2. The second integral can be evaluated as follows:

$$\int_{z_1}^{z_2} mgdz = mg(z_2 - z_1)$$

where the acceleration of gravity has been assumed to be constant with elevation. By rearranging:

$$\int_{z_1}^{z_2} Rdz = \frac{1}{2}m(V_2^2 - V_1^2) + mg(z_2 - z_1)$$



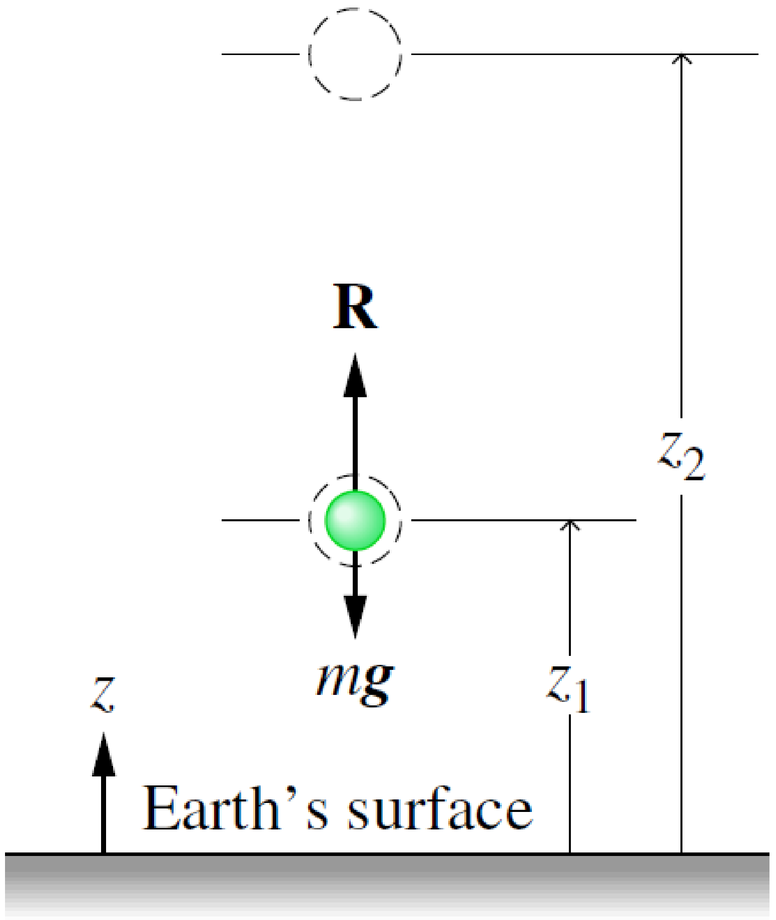
Subtheme 1.2: Work and Potential Energy

- The quantity mgz is the gravitational potential energy, PE. The change in gravitational potential energy, ΔPE, is:

$$\Delta PE = PE_2 - PE_1 = mg(z_2 - z_1)$$

The units for potential energy in the SI system are the same as those for kinetic energy and work.

Potential energy is associated with the force of gravity and is, therefore, an attribute of a system consisting of the body and the earth together.



Subtheme 1.3: Conservation of Energy in Mechanics

- The total work of all forces acting on the body from the surroundings, equals the sum of the changes in the kinetic and potential energies of the body
- The conservation of energy principle can be reinforced by considering the special case of a body on which the only force acting is that due to gravity.
- Under these conditions, the sum of the kinetic and gravitational potential energies remains constant

Subtheme 1.3: Conservation of Energy in Mechanics

- The notion that energy is conserved underlies this interpretation. The interpretation of the conservation of energy principle can be reinforced by considering the special case of a body on which the only force acting is that due to gravity, for than the right side of the equation vanishes, and the equation reduces to:

$$\frac{1}{2}m(V_2^2 - V_1^2) + mg(z_2 - z_1) = 0$$

$$\frac{1}{2}mV_2^2 + mgz_2 = \frac{1}{2}mV_1^2 + mgz_1$$

Under these conditions, the sum of the kinetic and gravitational potential energies remains constant. This equation also illustrates that energy can be converted from one form to another: For an object falling under the influence of gravity only, the potential energy would decrease as the kinetic energy increases by an equal amount.

Subtheme 1.4: Thermodynamic definition of Work

- The work W did by, or on, a system evaluated in terms of macroscopically observable forces and displacements is:

$$W = \int_{s_1}^{s_2} \boldsymbol{F} \, . \, d\boldsymbol{s}$$

This relationship is important in thermodynamics and is used to evaluate the work done in the compression or expansion of gases (or liquids), the extension of a solid bar, and the stretching of a liquid film.

However, thermodynamics also deals with phenomena not included within the scope of mechanics, so it is necessary to adopt a broader interpretation of work.

A particular interaction is categorized as a work interaction if it satisfies the following criterion, which can be considered the thermodynamic definition of work: Work is done by a system on its surroundings if the sole effect on everything external to the system could have been the raising of a weight.

Subtheme 1.4: Thermodynamic definition of Work

- Notice that the raising of weight is, in effect, a force acting through a distance, so the concept of work in thermodynamics is a natural extension of the concept of work in mechanics.

- However, the test of whether a work interaction has taken place is not that the elevation of weight has taken place, or that a force has acted through a distance, but that the sole effect could have been an increase in the elevation of a weight.

- Work is a means of transferring energy. Accordingly, the term work does not refer to what is being transferred between systems or to what is stored within systems. Energy is transferred and stored when work is done.

Subtheme 1.4: Thermodynamic definition of Work

- Engineering thermodynamics is frequently concerned with devices such as internal combustion engines and turbines whose purpose is to do work. Hence, in contrast to the approach generally taken in mechanics, it is often convenient to consider such work as positive. That is,

$W > 0$: work done by the system
$W < 0$: work done on the system

- This sign convention is used throughout the course. To evaluate the integrals, it is necessary to know how the force varies with the displacement. This brings out an important idea about work: The value of W depends on the details of the interactions taking place between the system and surroundings during a process and not just the initial and final states of the system.

It follows that work is not a property of the system or the surroundings. Also, the limits on the integrals mean “from state 1 to state 2” and cannot be interpreted as the values of work at these states. The notion of work at a state has no meaning, so the value of this integral should never be indicated as: $W_2 - W_1$.

Subtheme 1.4: Thermodynamic definition of Work

- The differential of work, δW, is said to be inexact because, in general, the following integral cannot be evaluated without specifying the details of the process

$$\int_1^2 \delta W = W$$

- On the other hand, the differential of a property is said to be exact because the change in property between two particular states depends in no way on the details of the process linking the two states. For example, the change in volume between two states can be determined by integrating the differential dV, without regard for the details of the process, as follows

$$\int_{V_1}^{V_2} dV = V_2 - V_1$$

where V_1 is the volume at state 1 and V_2 is the volume at state 2. The differential of every property is exact. Exact differentials are written, as above, using the symbol d. To stress the difference between exact and inexact differentials, the differential of work is written as δW. The symbol δ is also used to identify other inexact differentials encountered later.

Subtheme 1.4: Thermodynamic definition of Work

Other types of work (for example, electrical work), which we shall call either non-expansion work or additional work, have analogous expressions, with each one the product of an intensive factor (the pressure, for instance) and an extensive factor (the change in volume). Some are collected in table:

Type of Work	W	Comments	Units
Surface expansion	$\gamma d\sigma$	γ is the surface tension $d\sigma$ is the change in the area	N/m m^2
Extension	$f dl$	f is the tension dl is the change in length	N m
Electrical	ΦdQ	Φ is the electric potential dQ is the change in charge	V C

Subtheme 1.4: Thermodynamic definition of Work

- A particular interaction is categorized as a work interaction if it satisfies the following criterion, which can be considered the thermodynamic definition of work: Work is done by a system on its surroundings if the sole effect on everything external to the system could have been the raising of a weight
- Notice that the raising of weight is, in effect, a force acting through a distance, so the concept of work in thermodynamics is a natural extension of the concept of work in mechanics
- However, the test of whether a work interaction has taken place is not that the elevation of weight has taken place, or that a force has acted through a distance, but that the sole effect could have been an increase in the elevation of a weight

Subtheme 1.4: Thermodynamic definition of Work

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- This brings out an important idea about work: The value of W depends on the details of the interactions taking place between the system and surroundings during a process and not just the initial and final states of the system

Lesson 2: Modeling Expansion or Compression Work

- There are many ways in which work can be done by or on a system

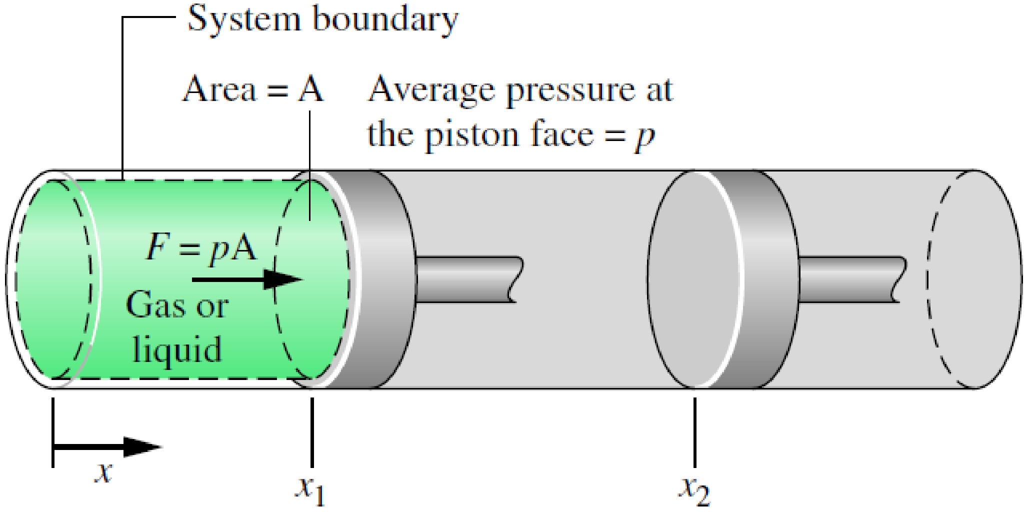
- The remainder of this section is devoted to considering several examples, beginning with the important case of the work done when the volume of a quantity of a gas changes by expansion or compression

Lesson 2: Modeling Expansion or Compression Work

- Let us evaluate the work done by the closed system shown in Figure consisting of a gas (or liquid) contained in a piston-cylinder assembly as the gas expands. During the process, the gas pressure exerts a normal force on the piston.

- Let p denote the pressure acting at the interface between the gas and the piston. The force exerted by the gas on the piston is simply the product pA, where A is the area of the transversal section of the piston face. The work done by the system as the piston is displaced a distance dx is:

$$\delta W = pAdx$$



Lesson 2: Modeling Expansion or Compression Work

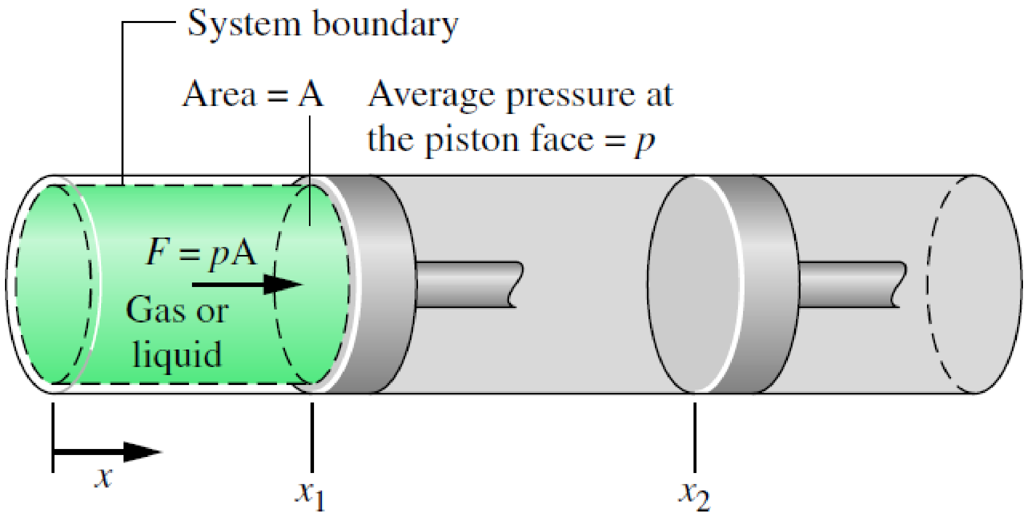
- The product Adx equals the change in volume of the system, dV.

- Thus, the work expression can be written as:

$$\delta W = pdV$$

- Since $dV > 0$ is positive when volume increases, the work at the moving boundary is positive when the gas expands. For a compression, $dV < 0$ is negative

- These signs agree with the previously stated sign convention for work.



Lesson 2: Modeling Expansion or Compression Work

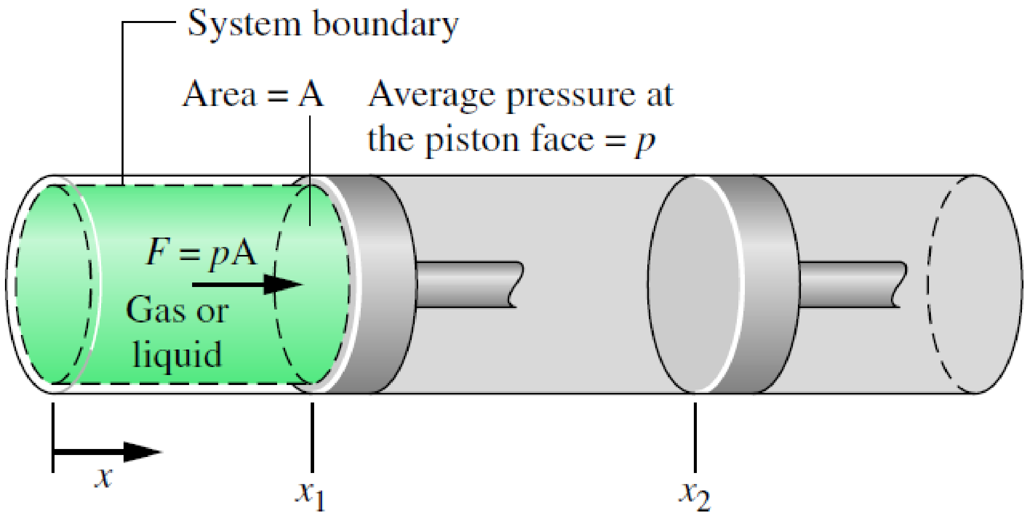
- For a change in volume from V_1 to V_2, the work is obtained by integrating:

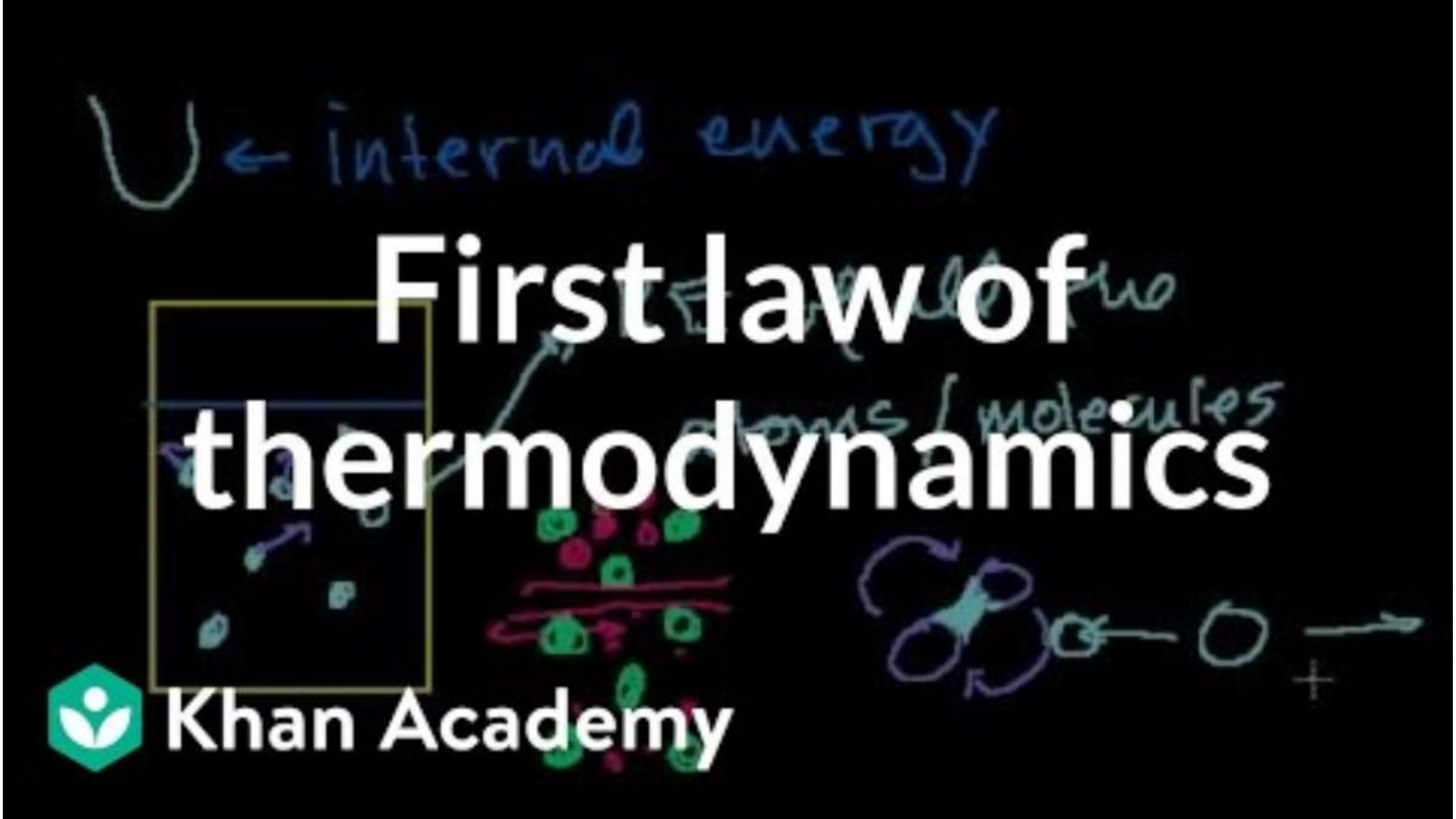
$$W = \int_{V_1}^{V_2} p dV$$

- This equation applies to systems of any shape provided the pressure is uniform with position over the moving boundary.

- By free expansion, we mean expansion against zero opposing force. It occurs when $p = 0$. According to the last equation, $W = 0$ for each stage of the expansion. Hence, overall:

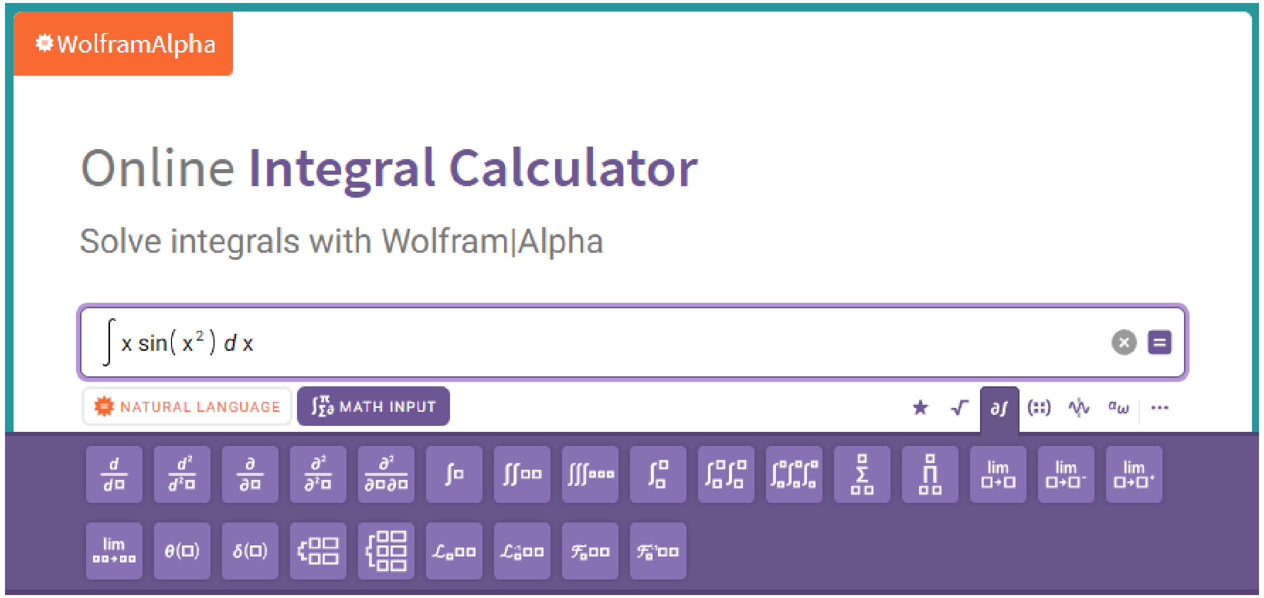
$$W = 0: \quad \text{Free expansion}$$




U ← internal energy
First law of thermodynamics
Khan Academy

Lesson 4: Practical Examples

- https://www.wolframalpha.com/calculators/integral-calculator/



- https://youtu.be/Xb05CaG7TsQ?si=fSOOGnvFNYimTtrl

Lesson 4: Practical Examples

An automobile has a mass of 1200 kg. What is its kinetic energy, in kJ, relative to the road when traveling at a velocity of 50 km/h? If the vehicle accelerates to 100 km/h, what is the change in kinetic energy, in kJ?

Results: $KE_1 = 115.74\ kJ$, $KE_2 - KE_1 = 347\ kJ$

Lesson 4: Practical Examples

An object whose mass is 400 kg is located at an elevation of 25 m above the surface of the earth. For $g = 9.78\ m/s^2$, determine the gravitational potential energy of the object, in kJ, relative to the surface of the earth.

Results: $97.8\ kJ$

Lesson 4: Practical Examples

A system with a mass of 5 kg, initially moving horizontally with a velocity of 40 m/s, experiences a constant horizontal deceleration of 2 m/s^2 due to the action of a resultant force. As a result, the system comes to rest. Determine the time, in s, the force is applied and the amount of energy transfer by work, in kJ.

Results: $\Delta t = 20\ s, W = -4\ kJ$